Development of an Expander for Residential Solar Thermal Power Generation

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By

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ABSTRACT

Currently, the U.S. is heavily dependent on the use of fossil fuels. In recent years, there has been a large push for increased implementation of renewable energy sources. Solar power is an attractive alternative energy source because of the virtually limitless supply of sunlight. Solar thermal power is created by concentrating sunlight to heat a working fluid and implementing the Rankine cycle to generate electricity. The systems are less suited for residential scale power generation because turbines that are used to expand the working fluid and turn the generators on a utility scale are do not scale well for small systems. The lack of a good option for a small-scale expansion device has led to the development of a new expander design originally proposed by Dr. Cantemir at the Ohio State University's Center for Automotive Research. Dr. Cantemir's concept was explored in this project by creating a solid model of his design. Next, a practical design for the expander was created based off of the concept and its six main parts; top cover, base, piston, joint, follower, and output shaft. The sizes, shapes, and positions of the inlet and outlet ports on the top cover were optimized to increase the expansion ratio of the device from 1.18 to 17.2. Practical features were added to the design to improve the functionality of the device such as: bearings at pivot and rotational points, a removable inspection plate, a redesigned joint, and two sealing methods for the piston.

ACKNOWLEDGEMENTS

I would like to first give a special thanks to Dr. Yann Guezennec for helping me have a direction through my research and getting me through the times when my progress was completely stuck. I would like to thank the previous members of the solar thermal team, Mike Nesteroff, Jake Wither, Nick Warner, and Brad Engel, for their previous research that helped guide me through my own research. Brad was especially helpful to me by walking me through the concept of the proposed expansion device and showing me how it functions. I would also like to thank the Ohio State University College of Engineering for awarding me a scholarship to perform the research presented in this thesis.

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CHAPTER 1: INTRODUCTION

1.1 Background

The greatest challenge facing this and future generations is how to solve the looming energy crisis. The world today runs on fossil fuels and one day in the not too distant future the available supply will not be able to meet the demand. In 2010, the production of electricity accounted for the greatest use of energy in the United States at 40% of the total energy consumed. Only 10% of the electricity was produced using renewable sources. [1]

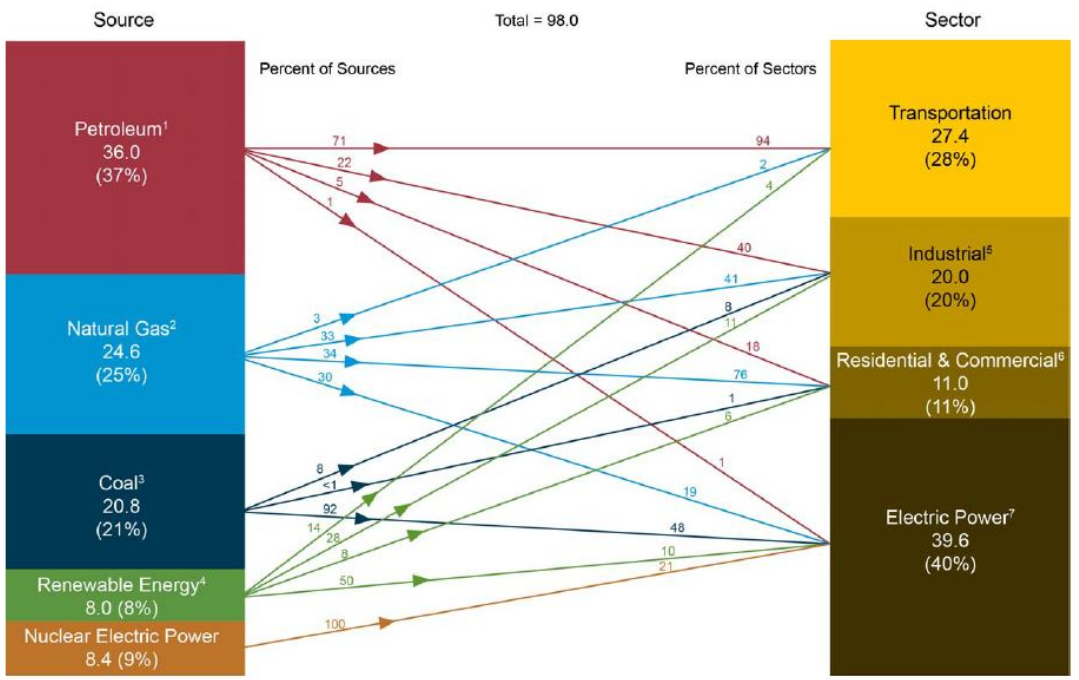

Figure 1: 2010 U.S. Energy Consumption by Source and Sector [1]

In 2010, 4,120 billion kilowatt-hours of electricity were generated in the United States. The leading source used to produce the electricity was coal which accounted for 44.9% of the total produced. Natural gas was the second greatest source accounting for 23.8%.

Hydroelectric power, wood, biofuels, and wind produce the majority of the renewable energy used. Solar energy is one renewable resource that is abundantly available. However, it has not been widely put into use because it is currently very expensive. Only 0.000316% of the electricity generated in 2010 was produced using solar thermal energy and photovoltaic (PV) cells. [1] Figure 2 shows the possible amount of power that could that could be generated from solar energy across the United States. Even though the potential amount of power produced from solar energy is lower in Ohio versus in New Mexico, there is still enough solar energy to make a large impact on reducing the amount of fossil fuels used.

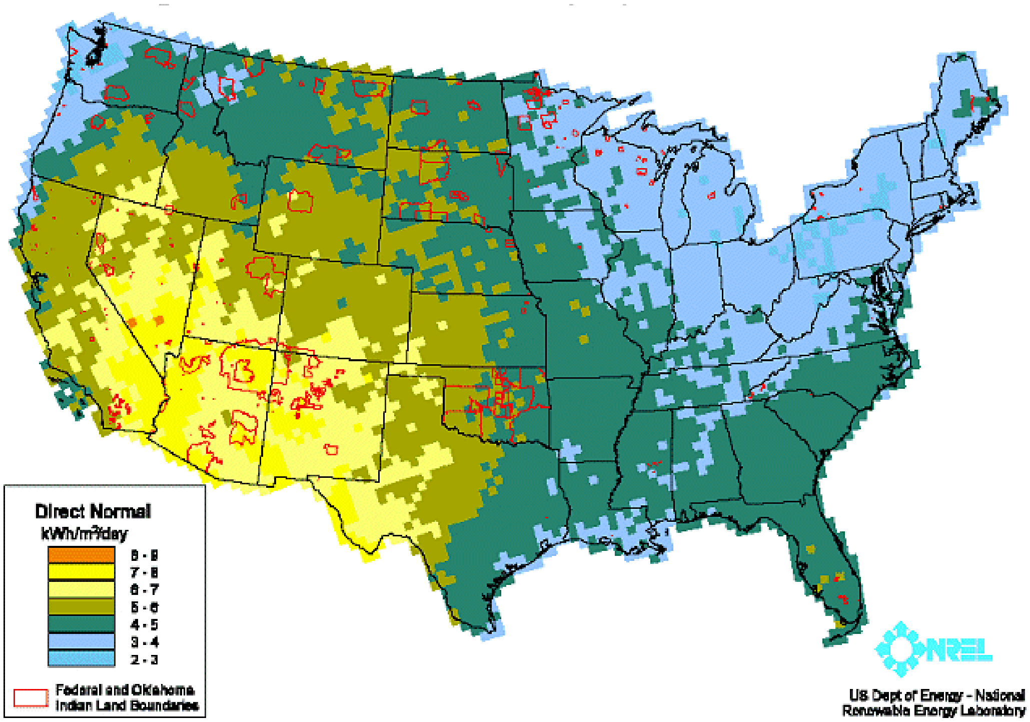

Figure 2: Concentrated Solar Power Resource Potential in the U.S. [2]

Photovoltaic cells are named after the photovoltaic effect which is the process of converting light to electricity. The PV effect was discovered in 1954 when it was found that an electric charge was generated when silicon was exposed to sunlight. The majority of PV cells today are still made from silicon. However, there have been advances made over the years. It is now possible to make flexible thin film PV cells using semiconductor materials that are only a few millimeters thick. The newest advances in PV technology open the possibility to solar inks that could be used much as the same way ink is used in conventional printing presses. There are also solar dyes and conductive plastics that are being developed. [3]

Photovoltaic cells are easily scalable for electricity generation at a wide range of total power output. They can be used to generate power as much as twenty to forty-eight megawatts at the utility and also be used at the residential scale only generating a couple kilowatts. The only major difference between the two systems would be the number of PV panels installed. This scalability has made PV cells the main choice for people that want to go green and generate their own electricity for their home. A typical residential PV system consists of PV cells that are generally mounted on the roof, a battery storage system to store the electricity so it can be used when it is needed, a battery controller to protect the batteries from overcharge or over-discharge, and an inverter to convert the direct current from the PV cells and batteries to alternating current that comes out standard outlets.

Figure 3: Photovoltaic Panel Array [4]

The major limiting factor to more widespread use of PV cells is the cost. From 1998 to 2010, the cost of a PV system has dropped 43%. Even with costs declining, it is still very expensive upfront to install a PV system on a home. In 2010, the average installed cost for a PV system was still $6.20 per watt. [5] This means that a three kilowatt system would cost $18,600. If prices continue to fall, PV cells might be a major source of power in the not too distant future.

Solar thermal systems are another way to harness the power of the sun's energy. Solar thermal systems that generate power are also called concentrating solar power (CSP) systems. CSP systems all operate using the typical Rankine cycle to generate electricity. A working fluid is heated up and converted to a vapor using mirrors that concentrate the sunlight onto a point. The vapor is then expanded. This is generally done through a turbine. The turbine turns a generator that produces electricity. After the working fluid goes through the turbine it is sent into a condenser to be converted back into liquid form. Then the fluid is pumped back to where the mirrors concentrate the sunlight in order to repeat the cycle. There are two common sunlight collection methods that are used on a utility scale; heliostats and parabolic troughs.

A heliostat is a large central collection tower onto which sunlight is concentrated. The heliostat is surrounded by a field of computer-controlled mirrors that follow the sun and reflect sunlight at precisely the correct angle so that it is directed at the heliostat. Temperatures can reach over 550°C at the collection tower. [6] Either water or a molten salt is usually heated. The molten salt helps to store the heat longer.

Figure 4: Heliostat Collection Tower [7]

A parabolic trough system consists of long rows of semicircular mirrors that concentrate the sunlight onto a tube which is located at the focal point. The tube which runs the length of the mirrors consists of a central pipe in which the working fluid flows directly through. The tube has a special solar absorbing coating to help it absorb as much solar energy as possible. The central tube is surrounded by an evacuated, larger diameter, anti-reflective glass tube. This tube helps to insulate the inner tube and reduce thermal losses. [8]

Figure 5: Parabolic Trough Collector [9]

Both solar thermal collection methods discussed generate electricity using the Rankine cycle. The general process is shown in Figure 6. First, heat is put into the system to boil a working fluid and convert it to a vapor. The pressurized vapor is then sent through an expansion device to expand the vapor and generate mechanical work. The mechanical work generally consists of turning a generator to generate electricity. After the vapor is sent through the expander, it is sent into a condenser in which the vapor is cooled and changed back into a fluid. From the condenser, the fluid is pumped back into the boiler to cycle the process. In a solar thermal power plant the heat used to boil the fluid is the heat from the concentrated sunlight.

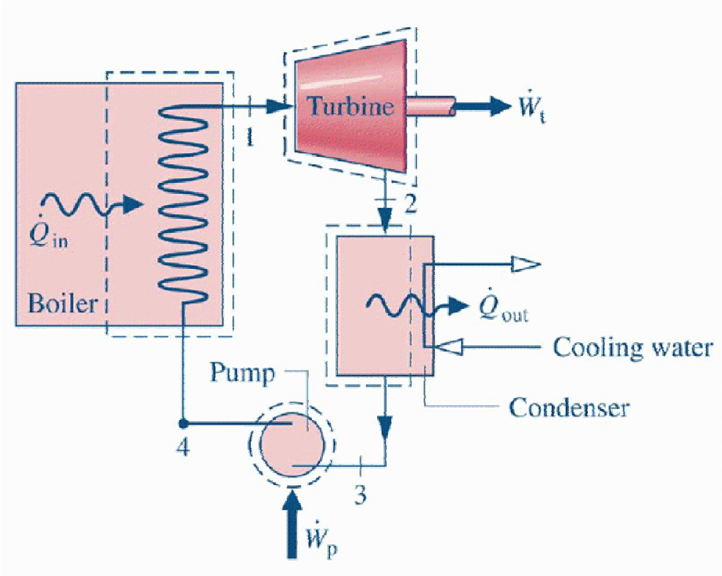

Figure 6: Rankine Cycle Diagram [10]

CSP systems have several advantages over photovoltaic cells. CSP plants are able to produce a more consistent power output than PV cells. The inertia of the expander helps to overcome lulls in sunlight when clouds pass by and block the sun. When clouds block the sun over a PV plant, the power output can drop very suddenly. CSP plants can also be used to generate electricity at night or on cloudy days. This can be accomplished two different ways. The working fluid is heated up by either using heat that is stored using molten salts or by burning natural gas to simulate the solar energy to maintain the Rankine cycle and keep the turbines spinning.

Electricity is generally only created using solar thermal energy on a utility scale system. The main residential uses of solar thermal energy are hot water heating, space heating, and pool heating. Many researching the implementation of a low temperature, small-scale solar thermal power system have noted that that there is a lack of options when it comes to selecting a small-scale expansion device for the system. Turbines are used in the utility scale systems, but they are not a viable option because they scale poorly. A small turbine would have a low efficiency and have to spin at tens of thousands of revolutions per minute to get the desire output power.

The most intriguing current expansion device has the most potential to be implemented in a small-scale CSP plant is a scroll expander. Scroll expanders are a modified version of the scroll compressor. Scroll compressors are widely used in residential air conditioning units. Scroll expanders operate using two spiral coils. One spiral is fixed in place and the other rotates around it as shown in Figure 7. The working fluid is expanded as it makes its way from the inside to the outside of the scroll expander.

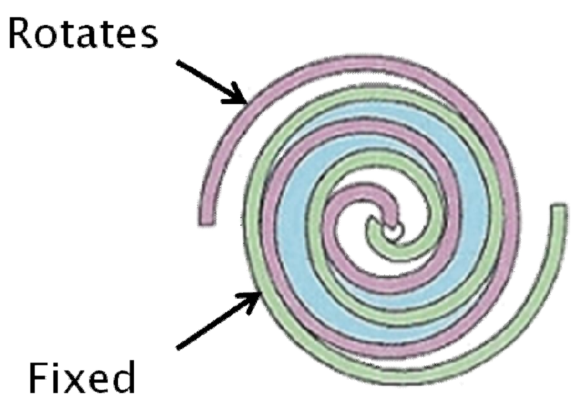

Figure 7: Scroll Expander Layout [11]

H. Wang, R.B. Peterson, and T. Herron tested a small-scale scroll expander in a low temperature organic Rankine cycle. They used R134a as their working fluid and pressurized it up to 2758 kPa. They found that it the expander could operate consistently with isentropic efficiencies of over 70%. Their scroll expander was able to output 1 kW of power. However, they did note that sealing the device was a little tricky. They also noted that the expander's performance varies as a function of speed, pressure ratio, and scroll sealing pressure. [12]

Sylvain Quolilin, Vincent Lemort, and Jean Lebrun also tested a scroll expander in an organic Rankine cycle. They found that the isentropic efficiencies varied in the range of 48% to 65%. They encountered similar issues with sealing the device completely like the previous group. However, there data shows that a scroll expander could be a viable option in a small-scale ORC. [13]

1.2 Motivation

This project was motivated by the search for new viable energy alternatives. Solar power shows much promise as a possible renewable energy source that could be widely implemented in the future. Today, there are only a limited number of options available for a home owner that wishes to generate their own electricity using solar energy. Photovoltaic cells are the popular choice available today due to their ease of installation and their high scalability. Residential solar thermal technology currently is focused around hot water heating and pool heating. By creating a residential-scale solar thermal power system, there is the opportunity for cogeneration meaning that not only would electricity be generated, but the waste heat could also be used for hot water heating, space heating, or even pool heating. By using the waste heat, the efficiency of the system is increased.

An issue in creating a small-scale, low temperature solar thermal power system that operates using an organic Rankine cycle (ORC) is selecting an expansion device. There are several options that are already produced that could work such as a scroll expander. However, the new design for an expansion device developed in this thesis could also work. By developing the device further, it can be benchmarked in the solar thermal power system against the other current expander options. If the device operates efficiently, it would have the opportunity to be implemented in numerous other applications.

1.3 Project Objective

The overall goal of this project is to aid in developing a low temperature solar thermal system with cogeneration that operates with a comparable efficiency to current photovoltaic cells. The specific focus of this project was to develop a practical design for a proposed expansion device that could be used in the ORC. First, a solid model of the conceptual device was to be created to gain a greater understanding of the operation of the device, the design parameters that can be altered, and the shortcomings that must be addressed to ensure that the device would be able to function. Next, a solid model of a practical design for the expander was to be created that would address the shortcomings of the original concept and operate at a desirable expansion ratio with proper inlet and outlet port timings.

CHAPTER 2: EXPANSION DEVICE CONCEPT

This section describes the original concept of the proposed device expansion device. The device was originally proposed by Dr. Codrin-Gruie Cantemir, a research scientist at the Ohio State University's Center for Automotive Research (CAR). Dr. Cantemir originally envisioned the device as a compressor. It was noted that the device could also operate as an expander by altering the inlet and outlets. Brad Engel did an initial analysis on the concept that warranted further development. [14]

2.1 Conceptual Design

The SolidWorks model shown in Figure 8 was created based off of Dr. Cantemir's original concept. Currently, there are no expanders that operate quite like Dr. Cantemir's concept. The device loosely operates similar to a cross between a rotary engine and a u-joint. The proposed expander has two chambers; an expansion chamber and a compression chamber. In Figure 8, the two chambers are shown at their extreme maximums.

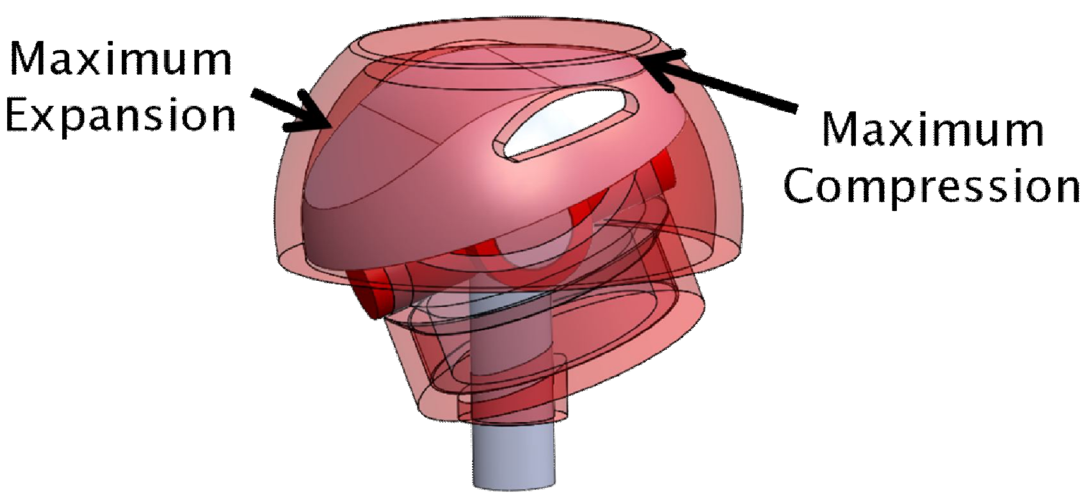

Figure 8: Model of Concept

The conceptual design consists of a top cover, a base, a follower, a joint, a piston, and an output shaft as shown in Figure 9. The top cover and base are fixed in place. The purpose of the base is to restrict the output shaft so that it can only rotate. The base also holds the follower at a 20° angle. The follower spins as guided by the base. The joint is fixed to the bottom of the piston. It links the piston to the "T"-shaped output shaft so that as the piston rotates the output shaft rotates at the same speed. The joint also has two shafts that are fixed to its sides that extend through the follower. The piston is a hemisphere shape with two faces cut out at the same 20° angle that the base guides the follower. The piston fits flush within the top cover. The inlet and outlet are the same shape and 180° apart in the concept proposed by Dr. Cantemir.

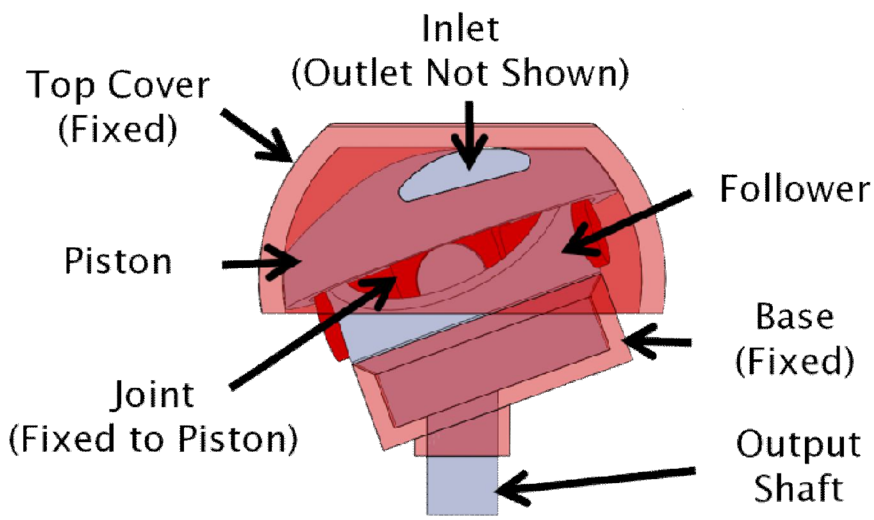

Figure 9: Parts the Expansion Device

2.2 Motion

The motion of the expander is unique. Figure 10 is a series of pictures that show the device as it goes through half of a revolution. The piston appears to wobble back and forth at the same time it is rotating. The wobbling is caused by follower which changes the angle of the joint. The piston's apex must be perpendicular to the joint for the device to wobble.

The two cavities are always acting in the opposite fashion as the device rotates. The green faced chamber in the series of pictures is the expansion chamber and the blue faced chamber is the compression chamber for the first 180° degrees of rotation. At 180° degrees of rotation, the two chambers swap roles so that what was the expansion chamber is now the compression chamber and vice versa. This is displayed in the 0° and 180° of rotation pictures. The device is in the same position at both angles of shaft rotation due to the symmetry of the device's rotation.

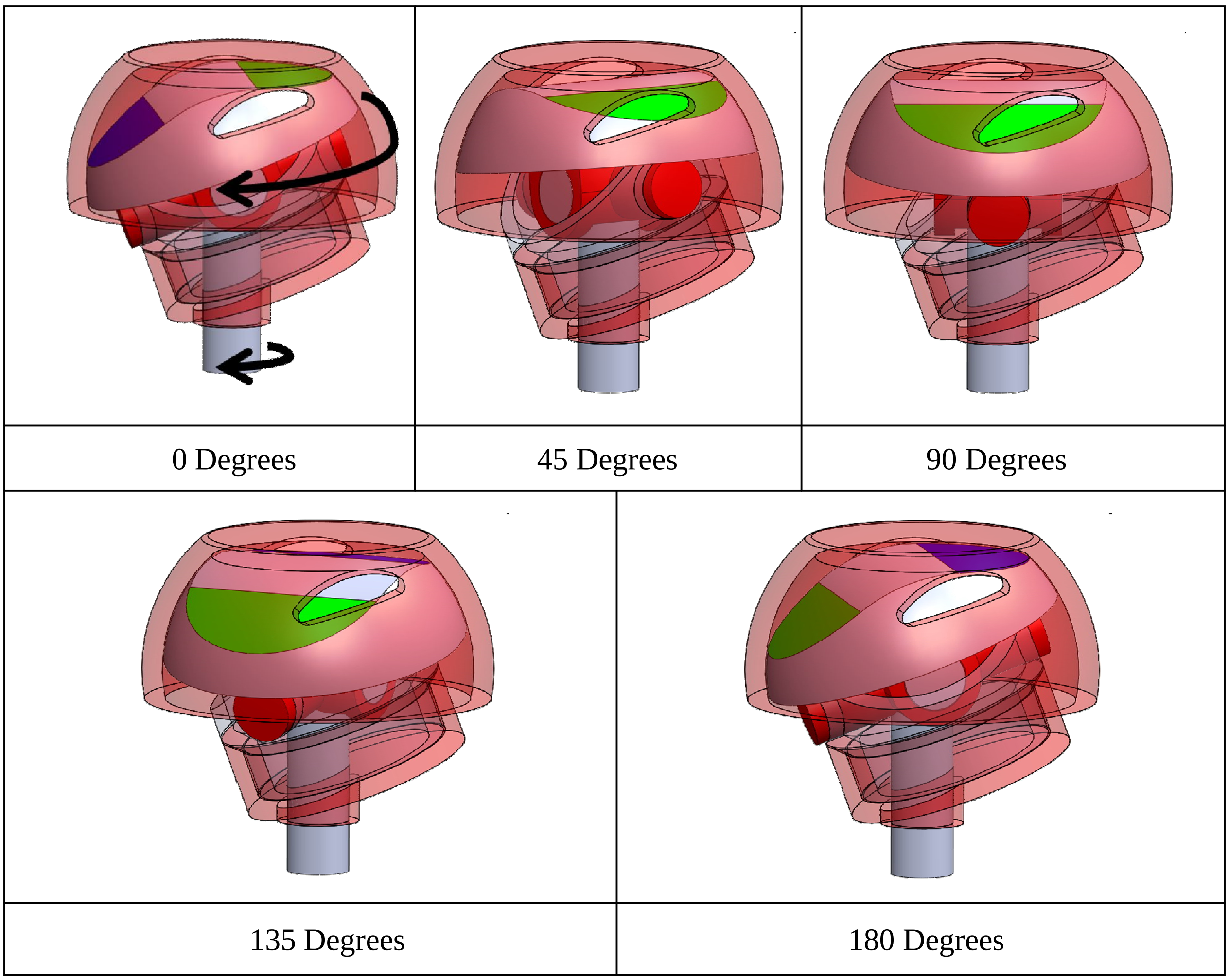

Figure 10: 180 Degree Rotation (Green=Expansion, Blue=Compression)

2.3 Shortcomings to be Addressed

The concept is good for helping to show the motion profile of the device. However, the concept is far from a practical design. There are several shortcomings that must be addressed in order for the expander to mechanically function as desired. The base and top cover are floating in the concept. They must be fixed together to keep the proper orientation. The joint must be redesigned to allow the output shaft to be more easily installed or removed. Bearings must be added at all of the rotating connection points to allow smooth operation. The device must have numerous seals to stop the working fluid from leaking. Finally, the inlet and outlet shapes, sizes, and positions must be optimized to allow the device to function as desired.

CHAPTER 3: FUNCTIONAL DESIGN

3.1 Functional Design Overview

Figure 11 shows two views of the current functional design. Overall, the current iteration remains very similar to the original conceptual design. The device's motion has not changed. There is still an expansion and a compression stroke happening simultaneously as the device rotates and the piston wobbles. There are still the same major components; a top cover, base, output shaft, follower, joint, and a piston. Figure 12 shows an exploded view of the device with the major components labeled.

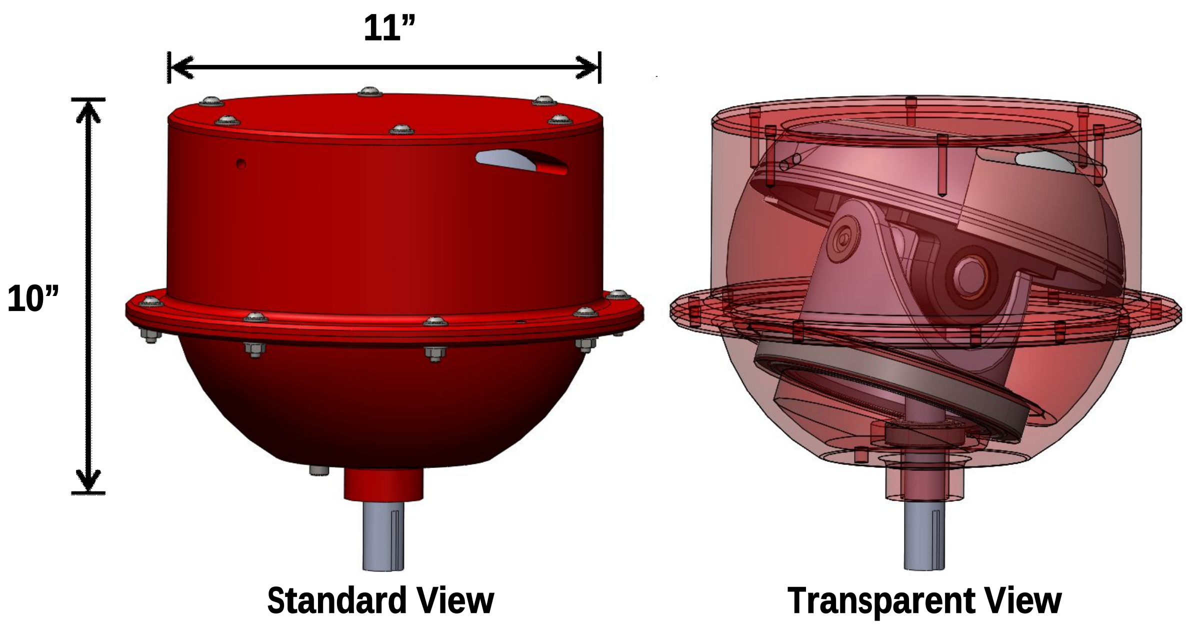

Figure 11: Functional Design

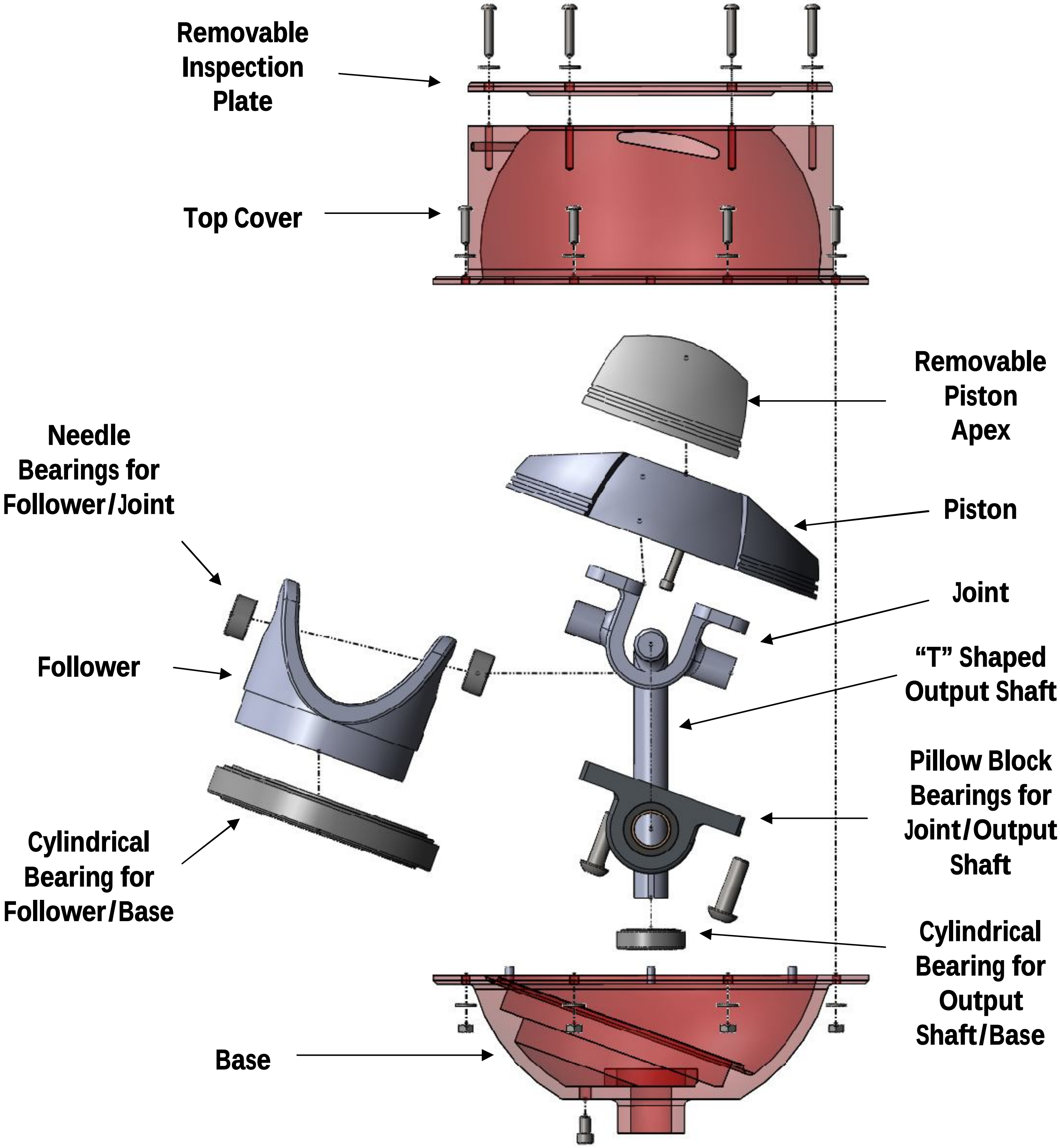

Figure 12: Exploded View of Expander

3.2 Design Parameters

There are several design and geometric parameters that have an effect on the expander's performance. The parameters of the expander are very similar to the parameters that can be varied in a traditional internal combustion (IC) engine. The piston diameter in the expander is similar to the bore size of a piston on an IC engine and has an effect on the maximum volume. The piston face angle correlates to the stroke of the piston in an IC engine. The piston face angle affects the volumes of the cavities and controls the angle at which the follower must be held. The inlet and outlet ports are like the intake and exhaust valves on an IC engine. The positions of the ports control the timing of when the ports are open and closed. The sizes of the ports control the mass flow rate into and out of the expander.

For this project, the piston diameter and piston face angle were kept at ten inches and twenty degrees respectively. This helped to eliminate a few of the design parameters and made it easier to focus on optimizing the port sizes, shapes, and locations.

CHAPTER 4: INLET AND OUTLET OPTIMIZATION

4.1 Volume Analysis

As described in previous sections, the motion of the proposed device causes the volumes of the cavities to increase or decrease in opposite fashions. Figure 13 shows a plot of both cavities' volumes as the piston rotates. In the first half of the revolution, cavity 1 is the expansion chamber. In the second half of the revolution, cavity 2 is the expansion chamber. The volume is never zero due to notch in the piston face.

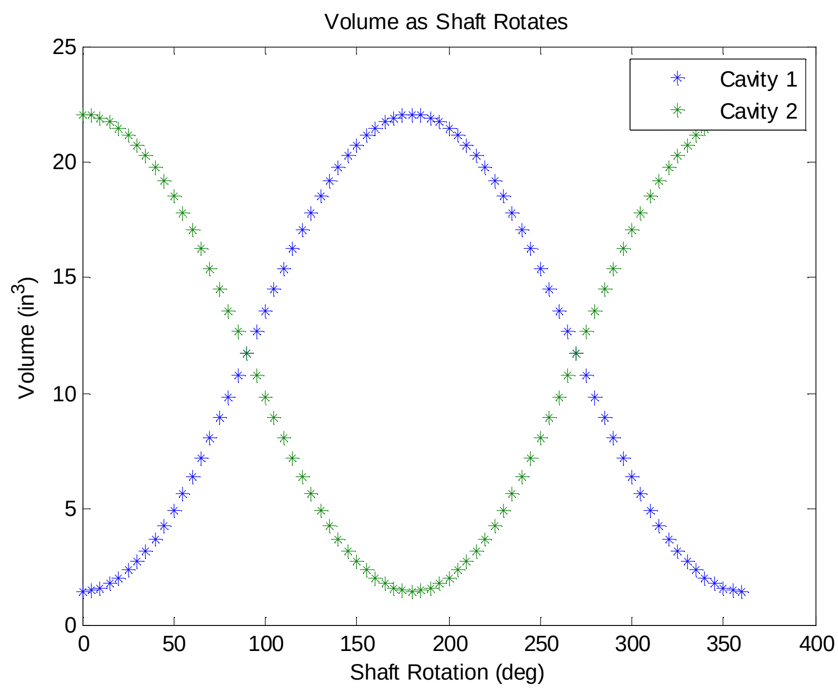

Figure 13: Cavity Volumes throughout Rotation

The cavity volumes were found using the SolidWorks model of the current device. Two parts were constrained so that they filled the cavity. An example of the cavity parts is shown in Figure 14. By checking the mass properties of each piece, the volume data for the cavity was easily found. By constraining the device and the cavity parts properly, the constraint that controls the shaft angle simply had to be changed and the parts that fill the cavity would be automatically updated. Then the mass properties of the cavity pieces just had to be check. The process was repeated over even intervals until the volume curve was well defined.

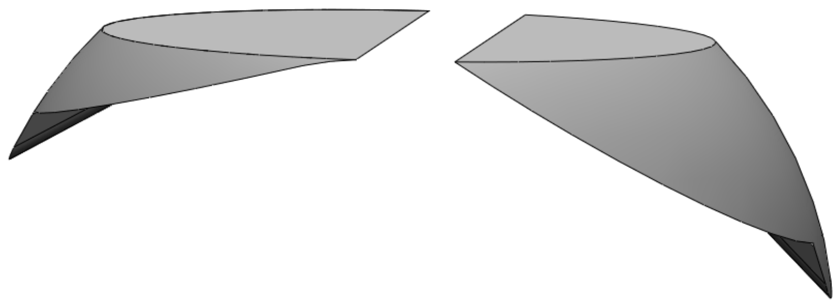

Figure 14: Example of Pieces used to Calculate Cavity Volume

The volumes appear to vary approximately sinusoidally. The curve is able to be quantified by curve fitting the data by using the "polyfit" command in Matlab to find the polynomial coefficients that best fit the data. Table 1 shows the coefficients found to fit the data. Figure 15 shows the curve fitted polynomial plotted on top of the cavities' volume data.

Table 1: Coefficients for Polynomial Curve Fit of Cavity Volumes

	P_1	P_2	P_3	P_4	P_5	P_6	P_7
Cavity 1	-2.5514e-13	2.7555e-10	-8.6985e-8	3.1099e-6	0.001610	-0.009619	1.1753
Cavity 2	2.3609e-13	-2.5498e-10	7.8806e-8	-1.6638e-6	-0.001715	0.01149	21.6585
General Equation: = + + + + + +							

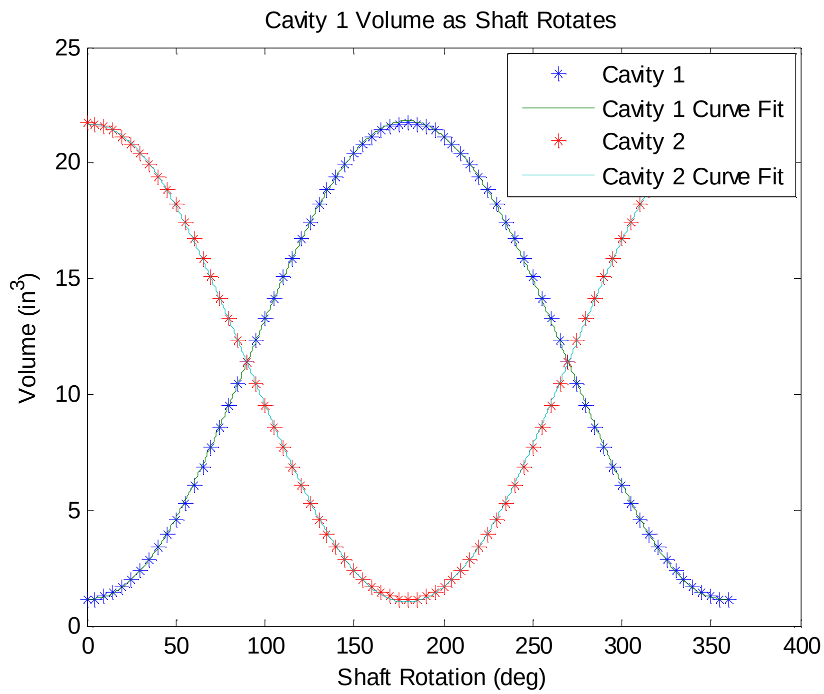

Figure 15: Curve Fits of Cavity Volumes

4.2 Expansion Ratio

One of the previously-stated goals of this project was to design the expander so that it operates a desirable expansion ratio. The expansion ratio is the maximum volume that the working fluid is expanded divided by its original volume. In the proposed expansion device, the expansion occurs during the period when the working fluid is trapped in the expansion cavity. Therefore, the expansion ratio is the cavity volume when the outlet port opens divided by the volume when the inlet port is closed.

The pressure ratio of an expander is the inlet pressure divided by the outlet pressure. It correlates closely to the expansion ratio. As the expansion ratio is increased the outlet pressure would drop meaning that the pressure ratio would increase. In Jake Wither's undergraduate thesis, he noted that the overall efficiency of the organic Rankine cycle increases as the pressure ratio of the expander is increased. [15] Therefore, a high expansion ratio would help to increase the overall efficiency of the system. A typical turbine has an expansion ratio in the range of 1.5 to 6. The goal is to optimize the inlet and outlet ports to create a device that has a significantly greater expansion ratio than a turbine to allow it to operate efficiently in a low temperature organic Rankine cycle.

4.3 Inlet/Outlet Analysis of Original Concept

In Brad Engel's initial analysis of the expander, he created theoretical volume curves that are similar to the curve found in the previous section of this report. He also made Figure 16 which shows a normalized volume curve for one of the compartments with functions also plotted that show when the inlet and outlet (exhaust) ports open and close. In this figure, the inlet port is opened between 340° and 20° of output shaft rotation when the compartment's volume is at its lowest. The exhaust port is opened between 160° and 200° when the compartment's volume is at its greatest. [14]

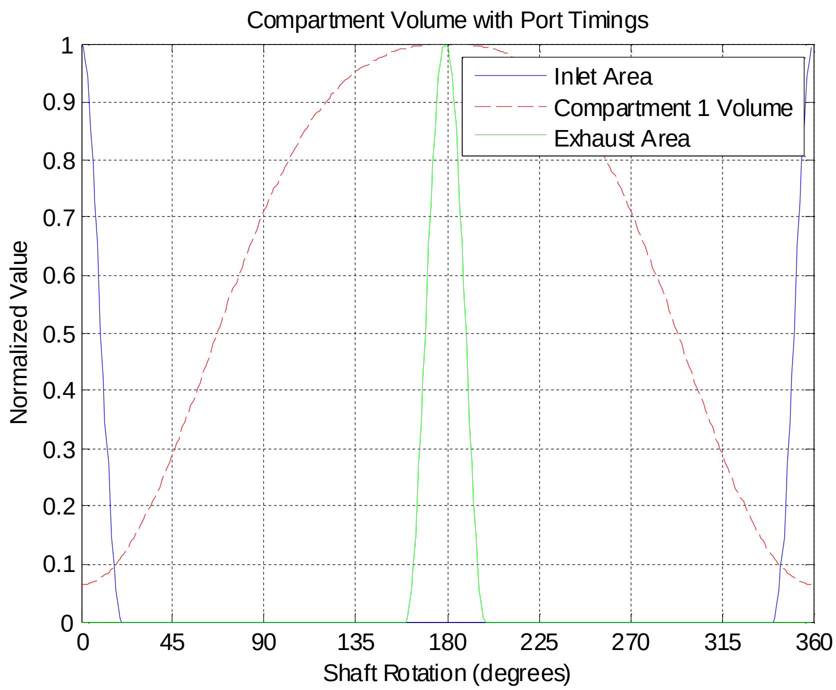

Figure 16: Normalized Cavity Volume and Port Openings as a Function of Shaft Rotation Angle [14]

The general position and duration of the inlet opening is very favorable. It is important to close the inlet port before the sharp increase of the compartments volume to take advantage of the majority of the expansion stroke. The outlet port should open when the volume of the compartment is at its maximum or very close to it for the same reason. However, the outlet should remain open for the duration of the compression stroke. The conceptual outlet function shown in Figure 16 would be adequate if there was some way to ensure that all of the working fluid does flow out of the device. If any of the working fluid was left in the compartment after the outlet closed, it would be compressed. The device would not operate as efficiently because some of the work that is meant to be used to help turn the generator would go into compressing the working fluid. Therefore, it is important to have the outlet open during the entire compression stroke to ensure that the device is only expanding the working fluid and not compressing it.

4.4 Inlet/Outlet Optimization

The process of optimizing the inlet and outlet ports consisted of first testing when the inlet and outlet ports are open with the port shapes and positions shown on the original concept. The area of the port openings was collected using SolidWorks in a similar fashion to how the cavity volumes were found. Two parts were created that plugged the inlet and outlet openings. A cut was constrained on both parts to cut the entire plug away except for where it was opened to allow flow in or out of the cavities. The inside surface area of what was left of the plug was then measured using the measuring tool in SolidWorks. When the constraint that controls the output shaft's rotational angle was changed, the parts would automatically update and the new values could be measured. Enough data was collected to produce a smooth plot of the openings.

Figure 17 shows the normalized cavity volume with the normalized inlet and outlet open timing for oval-like openings as shown in the original concept. The shape works well for outlet port because it remains open for a decent portion of the compression stroke. However, the oval-like shape does not work as well for the inlet. As the plot shows, the inlet is open for the majority of the expansion stroke severely reducing the expansion ratio. The expansion ratio of this setup was only 1.18. This is much less than turbines and would not make this device worth constructing.

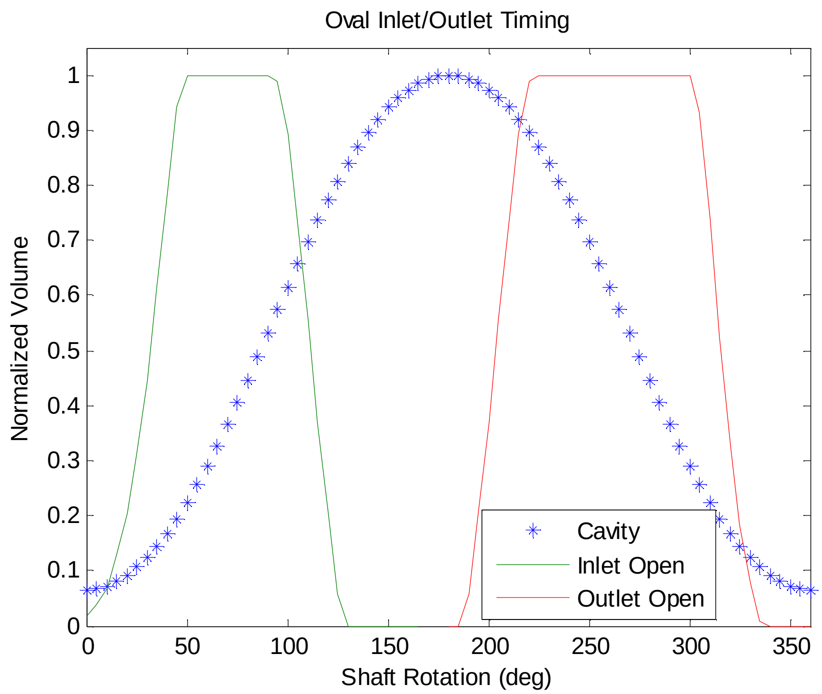

Figure 17: Normalized Cavity Volume and Original Port Openings as a Function of Shaft Rotation

From this figure, it was determined that the original oval-like port shape would be implemented for the outlet port. Figure 18 shows the optimized outlet port that was used in the current expander design. The outlet port is positioned where it opens just as the cavity reaches its maximum volume.

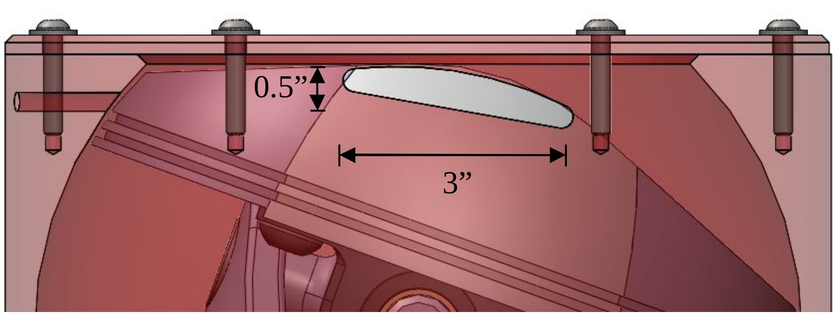

Figure 18: Optimized Outlet Port

The inlet port design had to be changed. The shape and position of the inlet port was varied to see what the different effects that the changes had on the inlet's timing. It was noted that in order to have the inlet open timing centered with the minimum cavity volume the port had to be positioned so that it was centered with the lowest volume roughly 90° from the outlet port. However, the various shapes and sizes had no real effect on shortening the time the inlet would be open due to the rotation and wobbling of the piston.

These issues were overcome by modifying the piston. A notch was added at the center of each face to allow a small inlet hole to be lowered on the case so that it would only be open when the notch passes. The notch gives greater control over the device's operation. The width of the notch controls how long the inlet port will be open. The depth of the notch into the piston controls how much the minimum volume is offset from zero. The optimized inlet is shown in Figure 19 and Figure 20. The inlet was drilled at an angle to help use the momentum of the inlet flow to aid in turning the expander.

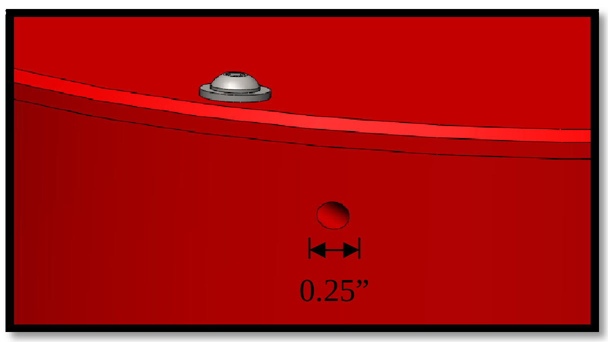

Figure 19: Optimized Inlet Port

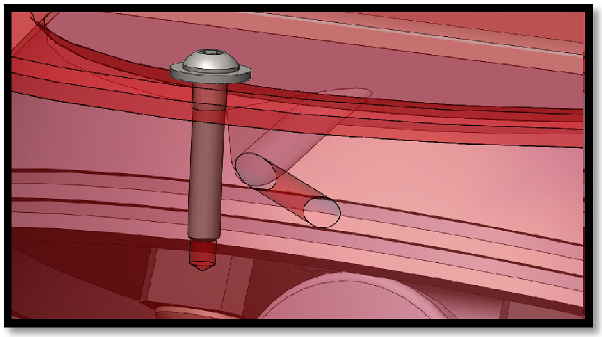

Figure 20: Optimized Inlet Port (Shown with Transparent Casing)

The results of the optimized openings are plotted in Figure 21. It shows that the inlet is open for 15° in a similar fashion to Brad Engel's inlet function. The outlet is open for 170°. Virtually, the entire expansion stroke is utilized to expand the working fluid to give the device an expansion ratio of 17.2 which is over 1450% greater than the expansion ratio before the ports were optimized.

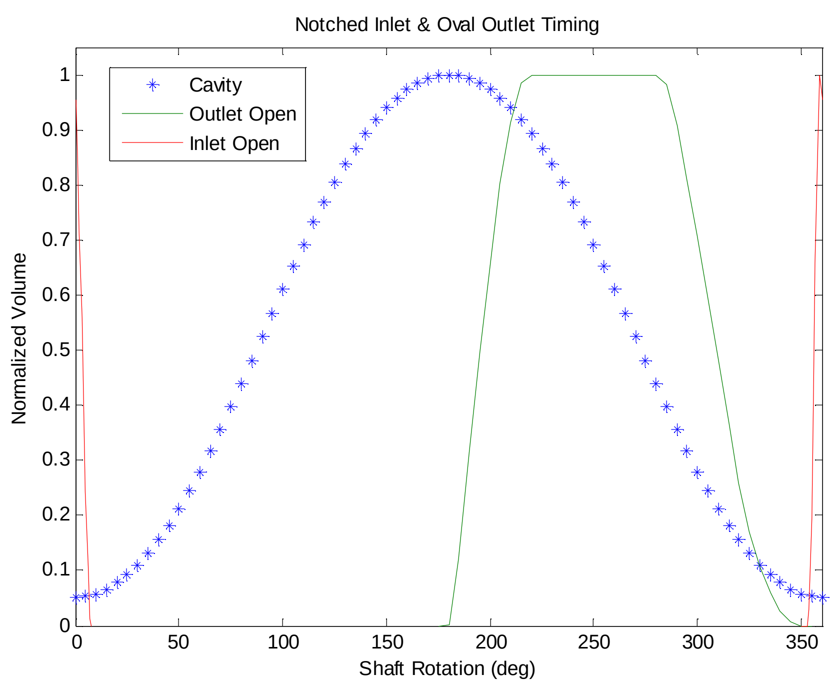

Figure 21: Normalized Cavity Volume and Optimized Port Openings as a Function of Shaft Rotation Angle

CHAPTER 5: DEVICE COMPONENTS

5.1 Case

The casing was redesigned for the functional design. The base still holds the follower at a 20° angle. However, it no longer is directly guiding the follower. There is a space for a cylindrical bearing to be press-fit into the base. The bearing allows the follower to rotate smoothly. The base still ensures that output shaft is vertical as well. Another press-fit cylindrical bearing is used to hold the output shaft vertical.

The issue of the top cover and lower base floating in the conceptual design was solved by extending a bowl-like structure around the base to build it up so that it can be bolted to the top cover using eight bolts around a flanged section on both pieces. The bolts are uniformly located around the flange to ensure that the device is tightly sealed in case of leaks from the expansion or compression cavities. Three pins, as shown in Figure 22, were also press-fit into the flanged ring around the base to ensure that the top cover be properly aligned with the base because it can only be assembled in one possible orientation.

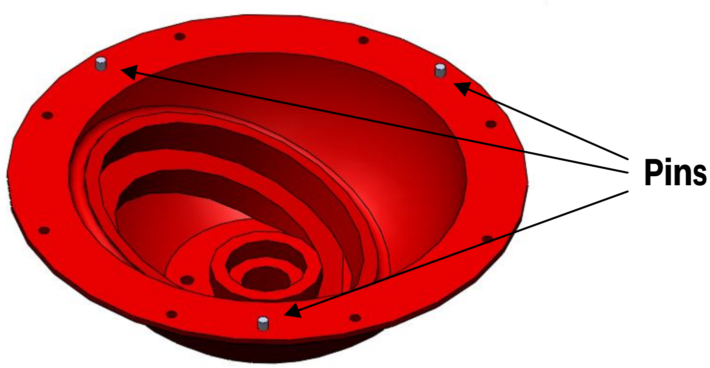

Figure 22: Base

It was noted that if there was an issue with the piston's rotation it could be difficult to see the real issue and diagnose the problem with the device fully assembled. To help look into the assembled device, a removable inspection plate was added to the top of the top cover. This plate can also help to serve a couple other purposes. The plate can be easily smoothed or coated in a low friction material where it comes into contact with the piston. By reducing the friction, the device will be able to operate more efficiently. The removable plate also makes demonstrating the device much easier. The device's motion is difficult to explain in words, but by removing the inspection plate it is possible to show how the volume of the two cavities varies as the device rotates.

5.2 Follower

The follower helps to give the device its characteristic wobbling motion. The follower assembly is shown in Figure 23. It has essentially the same design as that used in the original concept. The follower is press fit into a cylindrical bearing to allow it to rotate freely while being held by the base at a 20° angle. Needle bearings are used to connect the joint to the follower.

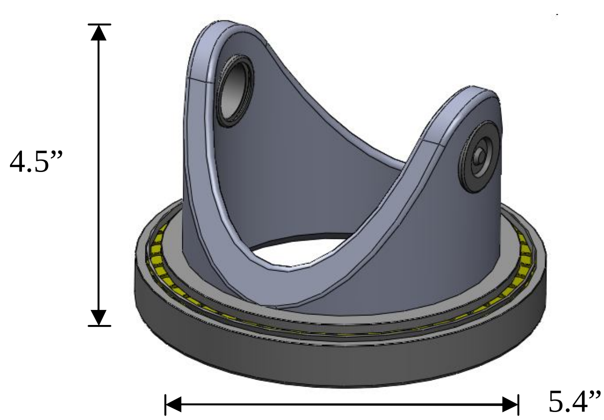

Figure 23: Follower Assembly

5.3 Joint & Output Shaft

The joint had to be redesigned to allow easier assembly. The current design for the joint and output shaft assembly is shown in Figure 24. It consists of the main joint piece, shown in Figure 25, two pillow blocks, and the “T”-shaped output shaft. The two pillow blocks connect the output shaft to the piston and allow the piston to wobble while the output shaft only rotates. The joint is fastened to the piston and surrounds the output shaft without actually contacting it.

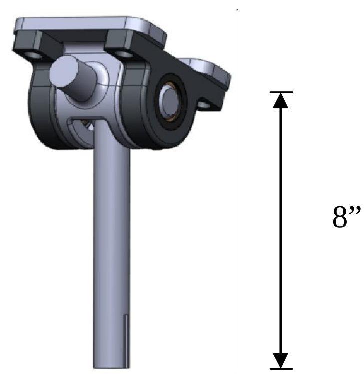

Figure 24: Joint, Pillow Block Bearings, and Output Shaft Assembly

The joint has two shafts that protrude from each side that are connected to the follower using needle bearings. These shafts along with the follower’s rotation control the wobble of the piston. To ease in manufacturing the joint piece, the shafts can be press-fit press fit into the joint piece structure and then welded in place. This process would allow the shafts to have a smoother finish than the rest of the joint piece which will help improve the operation of the needle bearings and increase the efficiency of the device.

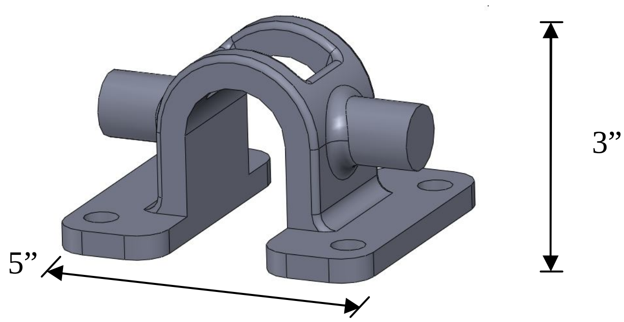

Figure 25: Joint

5.4 Piston & Seals

The piston, as shown in Figure 26, has kept the same basic shape as the original concept. Notches were added on both faces to control when the inlet is open. Chapter 4 explains more about why the notches were added and how they impact the device’s performance.

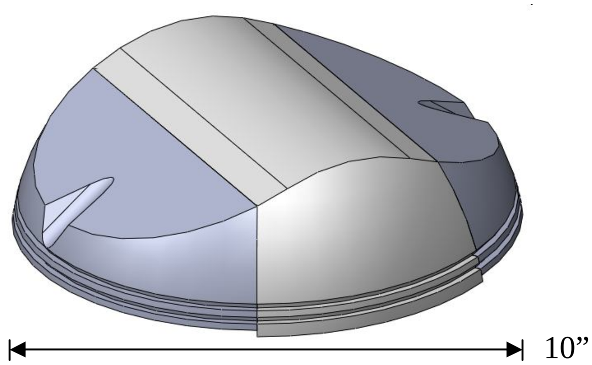

Figure 26: Piston

Sealing the piston is a unique task due to its complex geometry. There are two main areas that seals were needed. The piston had to be sealed near its base to prevent leakage into the lower casing of the device. A seal is needed that would be able to withstand rotation and translational motion. It was decided that traditional piston seals used on engine pistons would be well suited for this application and easy to acquire because of their wide availability. The apex and walls of the piston also had to be sealed to prevent leakage between the two cavities. The apex is unique because the contact between the piston and the top cover varies as the piston wobbles back and forth and rotates simultaneously. A removable piece for the piston’s apex, as shown in Figure 27, was designed to help seal the apex and walls. The sides of the removable piece are slightly bulged to ensure that there is contact with the top cover of the device. The apex is also slightly enlarged. There are several advantages to making the piece removable. Several different materials could be tested to see what works the best. It also makes repairing the device simpler and less costly. If the piece was to wear, the entire piston does not need to be replaced. The apex seal can be easily removed and a new piece can be bolted onto the piston.

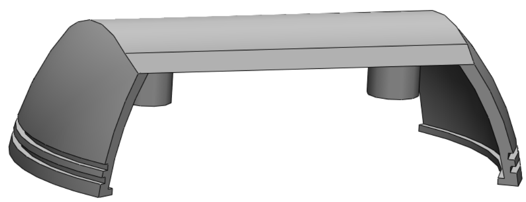

Figure 27: Removable Piston Apex

CHAPTER 6: SUMMARY AND FUTURE WORK

The issue with creating a low temperature residential solar thermal is selecting the expansion device to use in the organic Rankine cycle. A new design for a small-scale expansion device was developed for this project. Originally, the device was proposed by Dr. Cantemir at the Ohio State University Center for Automotive Research. The expander concept was first studied by creating a SolidWorks model based off of Dr. Cantemir's design. The characteristic motion of the expander was observed. The shortcomings of the concept consisted of: the casing, the joint piece, the lack of bearings, and sealing the device. In the final design, the casing was redesigned to have the top cover and base bolted to each other. Pins were added to the base to ensure that the top cover would be properly aligned when installed. The joint piece was also redesigned to allow easier assembly of the expander. Bearings were added at all of the pivot and rotational points on the device to ensure smooth operation. To seal the piston and two cavities, two sealing methods were implemented. The base of the piston was sealed using standard piston seals from an IC engine. The apex and walls of the piston were sealed using a removable part for the top of the piston. This part was slightly bulged from the piston to ensure that it contacts the inner walls of the top cover and seals the two cavities from one another.

There were several design parameters that influence the design and its performance; the piston diameter, the piston face angle, and the shapes, sizes, and positions of the inlet and outlet ports. For this design, the piston diameter and the piston face angle were chosen to be 10" and 20° respectively. The shape, size, and positions of the inlet and outlet ports were optimized by varying the parameters and comparing the plots of the timings that the ports were open overlaid on a plot of the volume of one of the cavities. From this plot the expansion ratio of the device was determined by dividing the volume of the cavity when the outlet opened by the volume of the cavity when the inlet closed. The goal was to maximize the expansion ratio. Through various trials, the effects of the varying each parameter was found and the expansion ratio was able to be increased from 1.18 originally to 17.2 with the optimized inlet and outlet ports. The piston was modified to include a notch that gives control over how long the inlet is open and the amount that the minimum cavity volume is offset from zero.

The next step in this research would be to optimize the size of the device by doing a thermodynamic simulation to ensure it could generate the power needed. With the dimensions selected, a prototype of the device could be built. It could be tested in a residential solar thermal power system. The device could be benchmark against a scroll expander to see which operates more efficiently. The final test could benchmark the solar thermal power system against photovoltaic panels to determine if the solar thermal system could be a viable cost-effective alternative.

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